MEASUREMENTS OF THE EFFECTIVE ELECTRODYNAMICAL PARAMETERS OF Nb MICROSTRIP RESONATOR[*]

V.A. Dravin, A.L. Karuzskii[#], A.E. Krapivka, N.A. Osipova, A.V. Perestoronin,

P.N. Lebedev Physical Institute of RAS, Leninsky prosp. 53, Moscow 117924, Russia

Abstract

Experimental method for simultaneous determination of the effective dielectric permittivity and the effective length (related directly to the effective magnetic permeability) of a microwave unit is developed. A method is based on the partial filling of a resonator cavity by the dielectric medium with low, controllably variable permittivity. For microstrip resonators partially filled with helium, the linear dependence of the reciprocal squared frequency on helium permittivity has been found experimentally. The proposed relations have related coefficients of this linear dependence to the effective permittivity and the effective length of microstrip resonator. As a result, the simple technique for a fast and precise determination of the effective permittivity and the effective length of a microwave unit has been proposed. This method needs neither special test fixtures and circuit standardization, nor additional model assumptions. Effective permittivities and effective lengths have been measured for Nb superconducting half-wave microstrip resonators in microwaves. Possibilities of the evaluation of superconducting material characteristics by the proposed technique are discussed.

1 INTRODUCTION

Passive microwave devices in a microstrip configuration are one of the most important applications of high-T_c superconductors (HTS). One of these applications is in planar oscillators [1], [2], [3]. To be competitive in a low phase noise with currently used dielectric resonator oscillators, HTS microstrip resonator should have quality-factor value (Q) of more than 50000 at frequencies of ~10 GHz [2]. The problems of design and development of high-Q microstrip resonators are connected with their sophisticated electrodynamics. This is in a great part due to the essentially semi-open type of microstrip resonators [4], [5]. Previous investigations of high-Q superconducting microstrip resonators [6], [7] have revealed the importance of resonator dispersion properties to the reduction in its losses. The found increase of the Q-factor over three orders of magnitude (from less than 10^3 to higher than 10^6) under slight variation of geometrical parameters, but with the fixed material parameters of a microstrip resonator (Fig. 1), is indicative of the predominant role of its spectral characteristics in loss mechanisms. It may be tentatively considered as an argument in support of the prediction [4] of higher Q-factors for non-radiating higher-order mode resonances. However, identification of the mode field configuration for a microstrip resonator is difficult. An experimental determination of the effective dielectric permittivity (ε_{ef}) and of the effective length (l_{ef}) for the given resonance mode can help in this problem since higher-order modes are rather dispersive in ε_{ef} [3], [8].
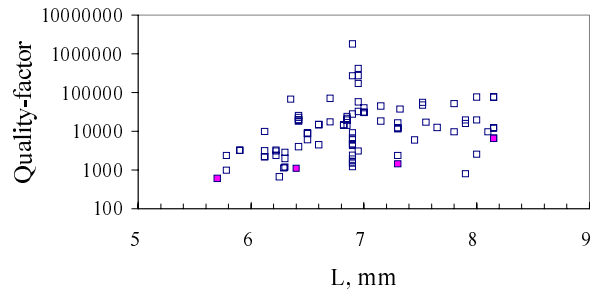

Figure 1: Quality-factor value of symmetric (open square) and asymmetric (closed square) linear microstrip Nb resonators on sapphire measured at T=2 K as a function of length of the strip (L)

We present an experimental method for simultaneous determination of the effective dielectric permittivity and of the effective length (related directly to the effective magnetic permeability μ_{ef}) of a microstrip resonator. These parameters define the resonant frequency f_p for a given mode of a resonator according to the relation $f_p^{-1} \sim (\mu_{ef} \, \varepsilon_{ef})^{1/2}$. Experimental values of $\varepsilon_{ef}^{1/2}$ and l_{ef} (the effective length $l_{ef} \sim \mu_{ef}^{1/2}$) of a resonator are of a great interest.

The method is based on the partial filling of a resonator cavity with helium - the low-loss dielectric medium, which possesses small, controllably variable relative permittivity (ε_{He}). The linear dependence of f_p^{-2} on ε_{He} has been found experimentally. It allows to introduce the relations which determine ε_{ef} and l_{ef} of a microstrip resonator from the coefficients of the linear dependence. Values of ε_{He} and l_{ef} and how these are affected by the geometry perturbation have been measured for Nb superconducting half-wave

microstrip resonators in microwaves. The proposed method may be useful in understanding the mode structure and loss mechanisms of high-Q microstrip resonators.

2 RESONATOR DESIGN AND MEASUREMENTS

Fig. 2 shows a representative shielded symmetric microstrip resonator used in measurements, which consists of niobium foil with a thickness of 15 μm sandwiched between two dielectric disks and forming a one-half wavelength strip. The $\lambda/2$ strip together with gap coupling microstrip transmission lines were assembled inside a cylindrical Nb cavity to form a shielded microstrip resonator.
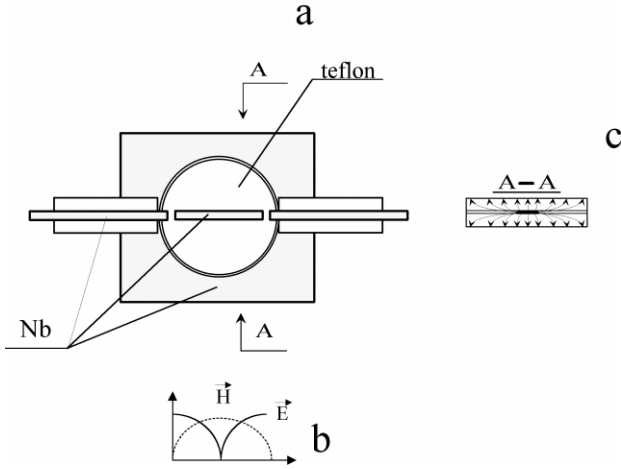

Figure 2: Scheme of the measuring microstrip niobium resonator. (a) Top view without cap of Nb shielding; (b) Spatial distribution of electromagnetic field amplitudes along the resonator; (c) Configuration of the electric field line in the cross-section

Microstrip lines coupled to and extracted electromagnetic energy within the cavity and were connected with a waveguide interface via microstrip-probe-into-waveguide transitions. Critical temperatures of superconducting niobium materials were of 9.2 K. The assembly was mounted in the helium bath of a cryostat. The boiling suppresser was used to prevent from helium boiling in the temperature range from 2.1 to 4.3 K. Sapphire, fused silica and teflon with relative dielectric constants (ε_d) of 10, 4 and 2, respectively, were tested as the dielectric laminae of a microstrip resonator. The residual volume of a resonant cavity was full of helium. (i) Asymmetric microstrip resonators with only a single lower sapphire disk, (ii) asymmetrically suspended microstrip resonators with two (upper and lower) teflon disks and a 1.6 mm gap between a top of the upper teflon lamina and a bottom plane of the Nb shielding cap, and (iii) strip resonators homogeneously filled with helium were measured also. The Nb-foil resonator in the last (iii)

situation was supported with narrow thin strips of transparent adhesive tape inside of the cavity. The actual length (l_0) of resonant strips was adjusted to have the fundamental-mode frequency of the order of 10 GHz..

To look at the influence of geometry perturbations on the effective parameters of a resonator, we compare the data obtained for the microstrip resonator with teflon laminae with data obtained for the same resonator, but with a 3 mm hole drilled in the upper teflon disk, and eventually, with data obtained for this resonator with the hole, but asymmetrically suspended (see above).

3 EXPERIMENTAL RESULTS

The resonant frequency f_p of a fundamental mode has been measured as a function of liquid-He temperature T in the range from 1.5 to 4.3 K for Nb microstrip and strip resonators described above. It has been found that the resonant frequency depends strongly on the temperature $f_p=f_p(T)$. For resonators with sapphire laminae, as an example, a temperature frequency coefficient (TFC) of order of $(5 \div 8) \times 10^{-4}$ K^{-1} has been measured at T=2 K. To find the reason of these TFC values, we will look at the effect of temperature dependent material properties. If we assume a deviation in the temperature of δT we can define a TFC or a fractional deviation in f_p as TFC=$(1/f_p) \times (\delta f/\delta T)$. Look at how temperature-dependent deviations in permittivities and dimensions of resonator components affect the TFC. The low-temperature TFC of pure sapphire at T=2 K is of 5×10^{-12} K^{-1} [9]. The TFC of Nb at T=2 K is dominated by deviations in the penetration depth and is of $4 \times 10^{-7} \div 10^{-9}$ K^{-1} [9], where the value 1×10^{-9} K^{-1} refers to the pure Nb. The observed TFC of the microstrip resonator appears to be much more than TFC of sapphire and Nb, so we can conclude that the helium permittivity has a dominant role in the temperature dependence of f_p.

Fig. 3 shows the f_p^{-2} data for symmetric and asymmetric microstrip resonators with different dielectric laminae and for a helium-filled strip resonator as a function of the helium permittivity or of the temperature: $f_p^{-2}=F_1(\varepsilon_{He})==F_2(T)$. The dependence $\varepsilon_{He}= \varepsilon_{He}(T)$ from [10] has been used for liquid He. Note the linear-on-ε_{He} scales for abscissa axes in Fig. 3. The data show that the dependence $f_p^{-2}=F_1(\varepsilon_{He})$ can be well approximated by a linear function of ε_{He} in the small-deviation interval of ε_{He} from 1.0490 to 1.0575.

4 ANALYSIS

The found linear dependence of f_p^{-2} on ε_{He} is a manifestation of the effects of fringing fields and an effective relative dielectric permittivity ε_{ef} for the mixed dielectric system like a microstrip resonator [4], [8], [11], [12]. This linearity allows to introduce the relations which determine the effective permittivity ε_{ef} and the effective length l_{ef} of a microstrip resonator from the coefficients of the linear dependence.
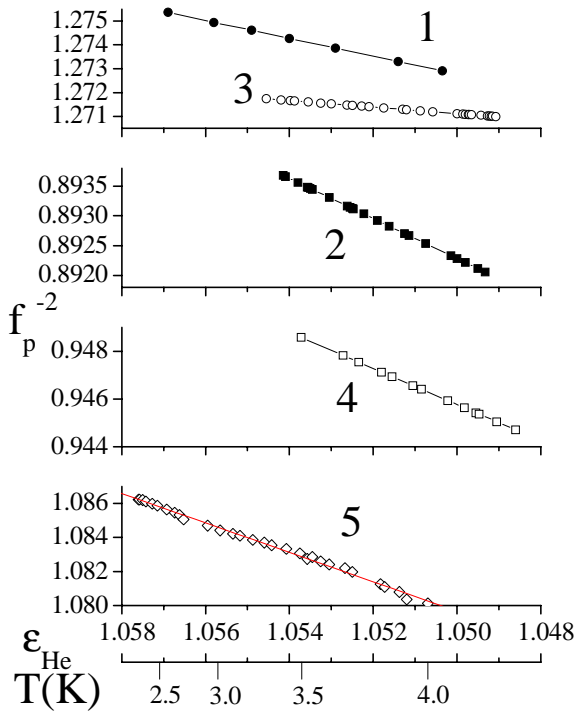
Figure 3: Inverse squared resonant frequency f_p^{-2} in 10^{20} Hz^{-2} units as a function of relative liquid-helium permittivity ε_{He} (linear abscissa scale) or of temperature T (dependence $\varepsilon_{He}=\varepsilon_{He}(T)$ from [10]) for symmetric microstrip resonators with dielectric laminae of sapphire (1), fused silica (3) and teflon (2), for asymmetric microstrip resonator with a single sapphire lamina (4) and for helium-filled strip resonator (5)

Dielectric loss tangents of helium and of solid dielectrics will be considered to be negligible. In essence, our resonator is a finite portion (l_0) of microstrip transmission line, terminated with large impedance mismatches (gaps and curvatures of shielding cavity). If we assume that a quasi-transverse electromagnetic wave [4], [8] propagates in the far wave zone of this transmission line we can define a resonant frequency of the half-wave-resonance mode using ε_{ef} and l_{ef} [11]:

$$f_p = c \,/(2l_{ef} \times \varepsilon_{ef}^{1/2})\qquad (1)$$

Here l_{ef} has the form $l_{ef} = l_0 + \Delta l$, where Δl is the effective length increment, $c=(\varepsilon_0\mu_0)^{-1/2}$ is the speed of light in vacuum, ε_0 and μ_0 are permittivity and permeability of vacuum. l_{ef} and ε_{ef} will depend on the resonant-mode-field structure. However, it is apparent that the effects of strip open-end fringing fields should dominate the l_{ef}, and the effects of strip-edge fringing fields should dominate the ε_{ef}. Hence we can define the effective partial volume v of the helium-penetrating electromagnetic field in a resonator using the following equation:

$$\varepsilon_{ef} \;=\; v\varepsilon_{He} \;+\; (1 - v)\varepsilon_d \qquad (2)$$

Using (2), we can re-express (1) as

$$f_p^{-2}=(2l_{ef}\,/\,c)^2 \times (v\varepsilon_{He}+ (1 - v)\varepsilon_d)=a\times \varepsilon_{He}+b \;, \qquad (3)$$

where a and b are $a =(2l_{ef}/\,c)^2 v$ and $b=(2l_{ef}/\,c)^2 v(1\text{-}v)\varepsilon_d$. For negligibly small temperature-dependent fractional deviations in ε_{He} which take place in experiment, we can consider l_{ef} and v, and hence a and b, to be a constant with reasonable accuracy. With these assumptions, data shown on Fig. 3 can be used to obtain the experimental values of l_{ef} and v or ε_{ef} from (3) and (2). The data obtained are listed in Table 1.

5 DISCUSSIONS AND CONCLUSION

The Nb strip resonator homogeneously filled with helium was used as a check on our measurements and data analysis procedure. The resulting values are v=0.99±0.02, ε_{ef}=1.07±0.01, l_{ef} =15.1±0.1 mm, Δl=1.2±0.1 mm. Note that the supporting narrow strips of adhesive tape slightly affect the derived parameters. The obtained values of v, ε_{ef}, l_{ef} and Δl for symmetric microstrip resonators are as follows: 0.193±0.0005, 1.866±0.002, 12.55±0.01 mm and 1.2±0.02 mm for teflon laminae, 0.63±0.05, 2.1±0.1, 9.7±0.2 mm and 1.5±0.2 mm for fused silica laminae, and 0.83±0.05, 2.4±0.5, 10.5±0.7 mm and 3.7±0.7 mm for sapphire laminae. Rather surprising results are derived for the asymmetric microstrip resonator with a single sapphire disk. These are v=0.98±0.01, ε_{ef}=1.16±0.02, l_{ef}=13.4±0.2 mm and Δl=7.7±0.2 mm.

Measured trends in behaviour of the effective parameters of microstrip resonators on sapphire (Fig. 4) show the increase of quality factor for certain high values of effective length increment Δl. It may be considered as evidence in support of the prediction [4] of higher Q-factors for non-radiating higher-order mode resonances.
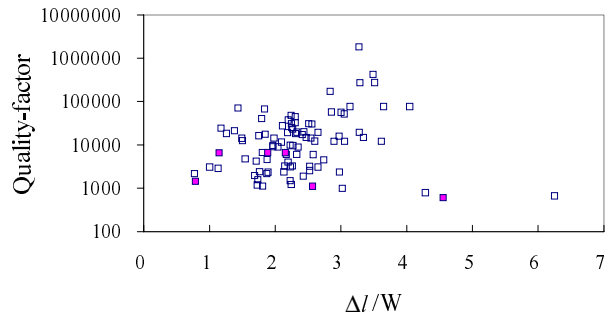

Figure 4: Q-factor of symmetric (open square) and asymmetric (closed square) linear microstrip resonators with Nb strips (cf. Fig. 1) in dependence of effective length increment (Δl) to strip width (W) ratio measured at T=2 K in 7.5-10 GHz range for different strip lengths (L=6-8 mm, W=1.5 mm)

Table 1: Measured effective parameters

Resonator type		ν	ε_{ef}	l_{ef}, mm	Δl, mm	l_0, mm
Dielectric materials	Resonator symmetry					
helium	symmetric	0.99 ±0.02	1.07 ±0.01	15.1 ±0.1	1.2 ±0.1	13.9
two teflon laminae, helium	symmetric	0.193 ±0.0005	1.866 ±0.002	12.55 ±0.01	1.2 ±0.2	11.35
two teflon laminae, helium	symmetric, with a hole	0.124 ±0.0005	1.876 ±0.002	12.24 ±0.01	0.9 ±0.2	11.35
two teflon laminae, helium	asymmetrically suspended, with a hole	0.280 ±0.0005	1.721 ±0.002	12.73 ±0.01	1.4 ±0.2	11.35
two fused silica laminae, helium	symmetric	0.63 ±0.05	2.1 ±0.1	9.7 ±0.2	1.5 ±0.2	8.15
two sapphire laminae, helium	symmetric	0.83 ±0.05	2.4 ±0.5	10.5 ±0.7	3.7 ±0.7	6.82
one sapphire lamina, helium	asymmetric	0.98 ±0.01	1.16 ±0.02	13.4 ±0.2	7.7 ±0.2	5.7

As a result of presented studies, the simple technique for a fast and precise determination of the effective permittivity and the effective length of a microwave unit can been proposed. The express-method can utilize the discontinuity of helium permittivity in a point of the liquid-vapor phase transition. This method needs neither special test fixtures and circuit standardization, nor additional model assumptions. Possibilities of the evaluation of superconducting material characteristics by the proposed technique are rather prominent and can be illustrated by the results of the investigations of the permittivity spatial dispersion and quasi-static effects in metals at microwave frequencies [13].

In conclusion, a method of the experimental determination of effective permittivities and effective lengths of microstrip resonators has been proposed. Measured values of ε_{ef} and l_{ef} may be useful in comparison of experimental data with results of rigorous and approximate theories [4], [11], [12] and in understanding of the resonant-mode-field structure in microstrips [4], [5], [8], as well as in evaluation of superconducting material characteristics.

6 REFERENCES

[1] A.P.S. Khanna, M. Schmidt and R.B. Hammond, "A SUPERCONDUCTING RESONATOR STABILIZED LOW PHASE NOISE OSCILLATOR", Microwave J., vol.34, pp.127-130, February 1991.

[2] Yu.M. Bogdanov, A.P. Gusev, Z.F. Kaplun, V.V. Malov, A.S. Tager, "Microwave oscillator with HTSC resonator", SPCT, vol.7, January 1994 [SFHT, vol.7, pp.170-173, January 1994].

[3] R.B. Greed and S.J. Hedges "AN INTEGRATED HIGH TEMPERATURE SUPERCONDUCTOR MICROWAVE SYSTEM/ CRYOCOOLER DEMONSTRATOR", GEC J. of Research, vol.12, No.2 (1995) 97-111

[4] E.I. Nefyodov, A.T. Fialkovskii, "STRIP TRANSMISSION LINES", 2nd ed., (in Russian), Moscow: Nauka, 1980, 312 p.

[5] I.E. Pochanina, V.P. Shestopalov, N.P. Yashina, "INTERACTION AND DEGENERATION OF EIGEN MODES IN OPEN WAVEGUIDE RESONATORS", Soviet Physics - Doklady (1991) [DAN SSSR, vol.320 (1991) 90-95].

[6] A.L Karuzskii, V.A. Dravin, A.S. Ignatyev, A.E. Krapivka, Yu.A. Mityagin, V.N. Murzin, A.V. Perestoronin, A.M. Tskhovrebov, "MICROSTRIP STABILIZED SEMICONDUCTOR QUANTUM WELL GENERATOR FOR MILLIMETER AND SUBMILLIMETER WAVELENGTH RANGE" in Int. Conf. on Millimeter and Submillimeter Waves and Applications III, M.N. Afsar, editor, Proc. SPIE 2842 (1996) 319-327.

[7] A.A. Beloushkin, A.S. Ignatyev, A.L. Karuzskii, V.N. Murzin, A.V. Perestoronin, A.M. Tskhovrebov, "MICROSTRIP STABILIZED SEMICONDUCTOR ASYMMETRICAL QUANTUM WELL STRUCTURE GENERATOR FOR MILLIMETER AND SUBMILLIMETER WAVELENGTH RANGE", Superlattices and Microstrustures, vol.22, No.1 (1997) 19-23.

[8] V.V. Zarubanov, A.S. Ilyinskii, "THE RESULTS OF APPLICATION OF THE SPECTRAL-DOMAIN APPROACH IN CALCULATING THE MICROSTRIP TRANSMISSON LINES", in "MATHEMATICAL MODELS OF APPLIED ELECTRODYNAMICS" (in Russian), V.I. Dmitriev and A.S. Ilyinskii, Eds. Moscow: Moscow University publishing house, 1984, pp.160-176.

[9] V.B. Braginskii, V.P. Mitrofanov, V.I. Panov, "SYSTEMS WITH A LOW DISSIPATION", (in Russian). Moscow: Nauka, 1985.

[10] V.I. Panov, V.A. Khvostikov, "PERMITTIVITY, MOLAR VOLUME AND CRITICAL PHENOMENA NEAR THE λ-POINT IN LIQUID HELIUM", Soviet Physics - JETP, vol.83, No.1, (1982) [Zh. Teor. Exp. Fiz., vol.83 (1982) 183-194].

[11] I. Wolf, N. Knoppik, "RECTANGULAR AND CIRCULAR MICROSTRIP DISK CAPACITORS AND RESONATORS" IEEE Trans. MTT, vol. 22, pp.857-864, October 1974.

[12] T. Itoh, "ANALYSIS OF MICROSTRIP RESONATORS" IEEE Trans. MTT, vol. 22, pp.946-952, November 1974.

[13] V.N. Apakina, V.A. Dravin, Yu.F. Eltsev, I.A. Istomin, A.L. Karuzskii, V.N. Murzin, A.V. Perestoronin, " SPATIAL DISPERSION AND NEGATIVE PERMITTIVITY EFFECTS IN SUPERCONDUCTORS " in Proc. 8th Workshop on RF Superconductivity, Abano Terme (Padova), Italy, October 6-10, 1997. V. Palmieri, A. Lombardi Eds. LNL-INFN (Rep)133/98, Vol.II, 352-356.